MODELING THE VOC EMISSIONS FROM INTERIOR LATEX PAINT APPLIED TO GYPSUM BOARD

Zhishi Guo, Roy Fortmann, and Steve Marfiak
Acurex Environmental Corp., PO Box 13109, Research Triangle Park, NC 27709, USA

Bruce Tichenor[1], Leslie Sparks, John Chang, and Mark Mason
US EPA, National Risk Management Research Laboratory, Indoor Environment Management Branch, MD-54, Research Triangle Park, NC 27711, USA

ABSTRACT

Small chamber emissions studies have demonstrated that the substrate played an important role in determining the rate of volatile organic compound (VOC) emissions from interior latex paint. An empirical source model for a porous substrate was developed that takes both the wet- and dry-stage emissions into consideration. Tests in the U.S. Environmental Protection Agency's (EPA) Source Characterization Laboratory showed that common interior surfaces such as gypsum board and carpet could adsorb significant amounts of latex paint VOCs from the air, and that they were re-emitted very slowly. An IAQ model incorporating the source model, an irreversible sink model, and the air movement data obtained from tracer gas tests made satisfactory predictions for the VOC levels in a test house.

INTRODUCTION

Over 1 billion gallons (~3.8×10^9 liters) of paint is sold in the United States each year. Of this paint, more than 50% is interior paint which, in recent years, has followed the trend towards water-based paint. Since the use of this paint can cause elevated concentrations of volatile organic compounds (VOCs) in indoor environments, exposure of building occupants to paint VOCs is of concern. It is generally believed that solvent evaporation from indoor coatings involves two physical processes: evaporation and internal diffusion, and that evaporation is the predominant mechanism early in the drying process (1, 2). A number of source models have been developed to represent the emission rate based on either or both mechanisms. Some examples are given in Table 1 with the symbols explained below: R= emission factor; M_0 = initial total VOC (TVOC) mass in the source; R_0, R_1, and R_2= initial emission factors; k, k_1, and k_2 = decay rate constants; t = time; k_m = gas-phase mass transfer coefficient; C_v = initial total vapor pressure; M = TVOC mass remaining in the source; C = TVOC concentration in indoor air; λ = film thickness or thickness of diffusion layer; M_D = VOC mass remaining in the source available for diffusion; M_{D0} = initial VOC mass in the source available for diffusion; and D = solid- or liquid-phase diffusion constant.

In the recent evaluation of VOC emissions from latex paint (3), we observed that the substrate played a significant role in determining the emission rates, and that some common interior surfaces such as carpet and gypsum board could strongly adsorb latex paint VOCs

---

[1] Current address: Rt 1, Box 302C, Macon, NC 27551, USA

from the air. This paper presents source and sink models for use in predicting the indoor concentrations when latex paint is applied to gypsum board.

Table 1. Selected Models for VOC Emissions from Indoor Coatings and Other Materials

Name	Expression	Type	Mainly Used For	Ref.
First-Order Model	$R = M_0 k e^{-kt}$	Empirical	Evaporation	(4)
Second-Order Model	$R = R_0 / [1+(k/\lambda) t R_0]$	Empirical	Both mechanisms	(5)
Double Expon. Model	$R = R_1 e^{-k_1 t} + R_2 e^{-k_2 t}$	Empirical	Both mechanisms	(6)
VB[a] Model	$R = k_m (C_v M/M_0 - C)$	Mass Transfer	Evaporation	(2)
Diffusion Model (D1)	$R = 0.632/\lambda M_D (D/t)^{1/2}$	Mass Transfer	Source Diffusion	(7)
Diffusion Model (D2)	$R = \pi^{-1/2}/\lambda M_{D0} (D/t)^{1/2}$	Mass Transfer	Source Diffusion	(8)

[a] VB: vapor pressure and boundary layer controlled emissions.

EXPERIMENTAL OBSERVATIONS

The test latex paint was purchased from a local store. According to the manufacturer's Environmental Data Sheet, the paint contained 3.7% of VOCs by weight. Our formulation analysis yielded a 4.5% VOC content, in which ethylene glycol was the dominant component (53%) followed by Texanol (30%), 2-(2-butoxyethoxy)ethanol (11%), propylene glycol (5%), and diethylene glycol (1%). In preparing the test specimens, the manufacturer's recommended method of application and film thickness were used.

A strong influence by substrate was observed in emissions testing conducted in 53-liter stainless steel environmental chambers: the peak concentration was much lower when the paint was applied to gypsum board than to stainless steel plates (Figure 1). Long-term tests [at 23°C, 50% relative humidity (RH), 0.5 air change per hour (ACH), and a 0.5 loading factor] showed that the emission factor for ethylene glycol from painted gypsum board was still 40 $\mu g/m^2/h$ at an elapsed time of 1 year. For individual VOCs, the gypsum board seemed to have a stronger effect on ethylene glycol and propylene glycol (Table 2).

The loss of latex paint VOCs to common interior surface materials (i.e., the sink effect) was studied in the same type of small chambers by first injecting the test compounds into the chamber at a constant rate for 7 days and then purging the chamber with clean air. Very strong adsorption was observed for every latex paint VOC tested (see Figure 2 as an example). Results from mass balance calculations showed that, after purging with clean air for 2 weeks, only 11% of ethylene glycol adsorbed by the gypsum board was re-emitted. The deposition velocity (i.e., first-order adsorption rate constant) was estimated from:

$$\text{Adsorption Rate} = W_a / (\Delta t\, S) = k_a C \qquad \ldots(1)$$

where W_a = total mass adsorbed by the sink material; Δt = duration of dosing period; S = area of the sink material; k_a = deposition velocity; and C = average chamber concentration (i.e., average outlet concentration). For the loss of ethylene glycol onto gypsum board and

carpet, the estimated deposition velocities were 1.5 and 2.4 m/h, respectively.

Table 2. Amounts of VOCs Emitted from Different Substrates in a 2-Week Testing Period

Compound	On Stainless Steel Plate			On Gypsum Board		
	Applied (mg/m^2)	Emitted (mg/m^2)	Fraction Emitted	Applied (mg/m^2)	Emitted (mg/m^2)	Fraction Emitted
Ethylene Glycol	3906	4023	103%	3855	582	15%
Propylene Glycol	378	337	89%	372	59	16%
Butoxyethoxyethanol	813	758	93%	801	194	24%
Texanol	2191	1961	90%	2160	1305	60%

MODEL DEVELOPMENT

The goal was to develop a source model that could predict the VOC emissions for both short- and long-term emissions from latex paint applied to porous materials such as gypsum board. The proposed model is a combination of the first-order decay model and a diffusion model (model D1 in Table 1) with an additional adjusting factor (or weighing factor):

$$R = M_V\, k \exp(-kt) + \alpha\, 0.632/\lambda\, M_D\, (D/t)^{1/2} \qquad ...(2)$$

where M_V = VOC mass available for evaporation; M_D = VOC mass available for diffusion; and α = adjusting factor. The adjusting factor we chose was $\alpha = (1- e^{-kt})^2$. As illustrated in Figure 3, adding α to the model is necessary because the original diffusion model gives unrealistically high emission rates early on but, in reality, the diffusion-controlled emissions can not become dominant until the paint film is dried. Since both λ and D in the diffusion model are unknown, we combined them to give a single parameter, $f_D = 0.632\, D^{1/2} / \lambda$ (diffusion constant), which bears the unit of $h^{1/2}$. Equation 2 can then be simplified to:

$$R = M_V\, k \exp(-kt) + \alpha\, f_D\, M_D / t^{1/2} \qquad ...(3)$$

where M_D is a variable and is governed by:

$$dM_D/dt = -\alpha\, f_D\, M_D / t^{1/2} \qquad ...(4)$$

The chamber concentration, C, can then be computed from:

$$dC/dt = L\, R - N\, C \qquad ...(5)$$

where L=the loading factor and N=air exchange rate. Equations 3 to 5 can be used in indoor air quality (IAQ) simulations but they must be solved simultaneously. Further simplification can be made to eliminate Equation 4. Since α only has an effect in a short period of time and will quickly approach 1 afterwards, we can set $\alpha = 1$ to obtain an

approximate solution to Equation 4 given that $M_D = M_{D0}$ when $t = 0$:

$$M_D = M_{D0} \exp(-2 f_D t^{1/2}) \quad \ldots(6)$$

Substituting Equation 6 into 3, we obtain the following expression for emission factor:

$$R = M_V k \exp(-kt) + \alpha f_D M_{D0} \exp(-2 f_D t^{1/2}) / t^{1/2} \quad \ldots(7)$$

This source model can be inserted directly into Equation 5 to compute concentrations. Numerical examinations showed that the error caused by this approximation of Equation 6 was insignificant.

MODEL EVALUATION AND PRELIMINARY VALIDATION

There are four parameters in this model: M_V, k, M_{D0}, and f_D. Since the sum of M_V and M_{D0} is the amount of VOC applied to the substrate, only one of them needs to be determined if the formulation of the product is known. Table 3 presents the estimated parameters for one chamber test. The model fits the data very well in the whole data range (Figure 4).

Table 3. Estimated Model Parameters for a Chamber Test

Compound	M_V (mg/m^2)	k (h^{-1})	M_D (mg/m^2)	f_{D0} ($h^{-1/2}$)
Ethylene Glycol	19.1	1.05	3304	0.00235
Propylene Glycol	21.8	0.0814	299	0.00374
Butoxyethoxyethanol	47.5	0.165	643	0.00203
Texanol	404	0.0635	1465	0.00173

Preliminary validation of the source model was made by painting the gypsum board walls of one bedroom in a test house with the latex paint tested in the small chambers and monitoring the VOC concentrations in three rooms for 1 month. The air exchange rate was determined by the tracer gas decay method (four tracer releases a day). The air flows through the air handling system were measured in the return grille and each register. The IAQ mass balance model used was:

$$V_i \, dC_i/dt = S_i R(t) + \sum Q_{ji} C_j - \sum Q_{ij} C_i - A_i k_s C_i \quad \ldots(8)$$

where V_i = volume of zone i; C_i = concentration in zone i; C_j = concentration in zone j; S_i = area of newly painted wall; R = emission factor calculated from Equation 7 (for source room only); Q_{ji} = air flow from zone j to zone i; Q_{ij} = air flow from zone i to zone j; A_i = area of the sink in zone i; and k_s = deposition velocity for wall loss (assumed to be same for all zones).

Using the model parameters obtained from small chamber testing and an average deposition velocity of 2.0 m/h for ethylene glycol, this IAQ model made reasonable predictions for the VOC concentrations in different zones (Figure 5).

DISCUSSION

One of the desirable features of the proposed model is that it uses actual VOC mass applied to the surface, which can be calculated from formulation analysis and the amount of paint applied. None of the existing empirical models gives realistic amounts of VOC available for emissions. For instance, the amount of ethylene glycol applied in a chamber test was 2332 mg/m^2, but the double exponential model gave an emittable mass of 429 mg/m^2; on the other hand, the second-order model would allow an infinite amount of VOC to be emitted. The other desirable feature of this model is that the parameters obtained from short-term testing can be used to predict the long-term emissions (Figure 6). The drawback of this model is that the first-order decay model used for the evaporation-controlled emissions is empirical. We are currently trying to replace it with a mass transfer model.

ACKNOWLEDGEMENT

The research described in this paper was funded by the U.S. EPA under Contract No. 68-D4-0005. The authors also wish to acknowledge the work of Mark Bero, Huei-chen Lao, Kenneth Krebs, and Nancy Roache of Acurex Environmental Corp. on this project.

REFERENCES

1. Sullivan, D.A. 1975. "Water and solvent evaporation from latex and latex paint films." *Journal of Paint Technology*. Vol. 47, pp. 60-67.

2. Tichenor, B.A.; Guo, Z.; and Sparks, L.E. 1993. "Fundamental mass transfer model for indoor air emissions from surface coatings." *Indoor Air*. Vol. 3, pp. 263-268.

3. Krebs, K.; Lao, H.C.; Fortmann, R.; and Tichenor, B. 1995. "Test methods for determining short and long term VOC emissions from latex paint." *Engineering solutions to indoor air quality problems*. Air & Waste Management Association, Pittsburgh. pp. 71-75.

4. Clausen, P. A. 1993. "Emission of volatile and semivolatile organic compounds from waterborne paints - the effect of the film thickness," *Indoor Air '93*. Vol. 2, pp. 567-572.

5. Clausen, P. A.; Laursen, B.; Wolkoff, P.; Rasmusen, E.; and Nielsen, P. A. 1993. "Emission of volatile organic compounds from a vinyl floor covering," *Modeling of Indoor Air Quality and Exposure*, ASTM STP 1205. pp. 3-13.

6. Colombo, A.; De Bortoli, M.; Knöppel, H.; Schauenburg, H.; and Vissers, H. 1990. "Determination of volatile organic compounds from household products in small test chambers and comparison with headspace analysis." *Indoor Air '90*. Vol. 3, pp. 599-604.

7. Hanna, S. R. and Drivas, P. J. 1993. "Modeling VOC emissions and air concentrations from the Exxon Valdes oil spill." *J. Air and Waste Manage. Assoc.*, Vol. 43, pp. 298-309.

8. Christianson, J.; Yu, J. W.; and Neretnieks, I. 1993. "Emission of VOC's from PVC-flooring - models for predicting the time dependent emission rates and resulting concentrations in the indoor air." *Indoor Air '93*. Vol. 2, pp. 389-394.

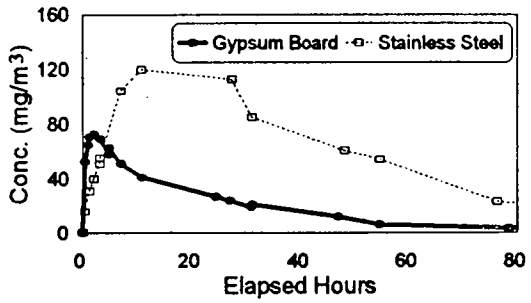

Figure 1. TVOC emissions from latex paint applied to different substrates

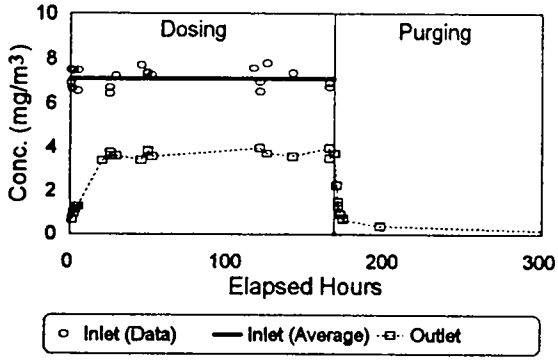

Figure 2. Adsorption of ethylene glycol by gypsum board in a 53-L chamber

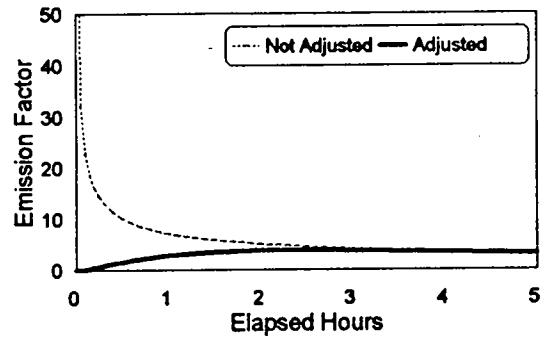

Figure 3. The role of the adjusting factor on diffusion-controlled emission rate

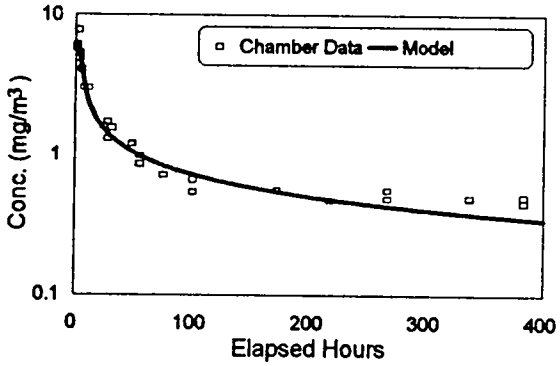

Figure 4. Modeling ethylene glycol emissions from painted gypsum board

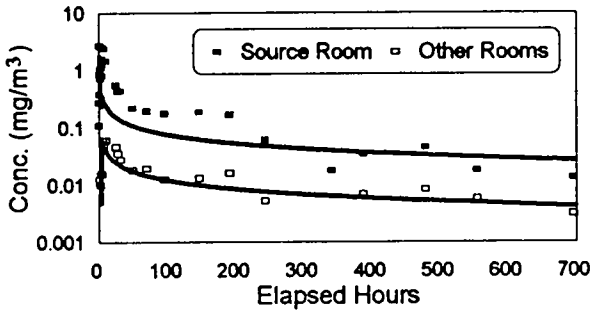

Figure 5. IAQ Simulation for the latex paint experiment in the test house (Solid lines are model predictions)

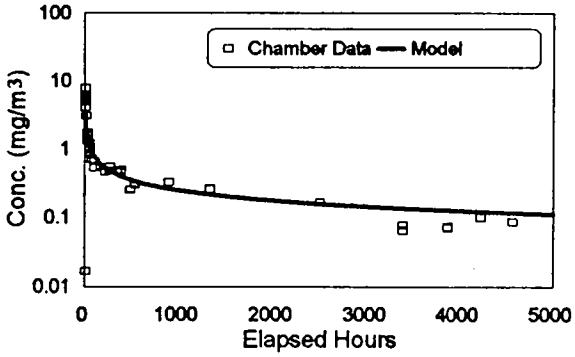

Figure 6. Prediction of long-term ethylene glycol emissions with model parameters obtained from short-term test

NRMRL-RTP-P-106

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RE
EPA/600/A-97/007		

4. TITLE AND SUBTITLE
Modeling the VOC Emissions from Interior Latex Paint Applied to Gypsum Board

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Z. Guo, R. Fortmann, and S. Marfiak (Acurex); and B. Tichenor, L. Sparks, J. Chang, and M. Mason(EPA)

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Acurex Environmental Corporation
P. O. Box 13109
Research Triangle Park, North Carolina 27709

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-D4-0005, Task 11

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Published paper; 1-4/96

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES APPCD project officer is Leslie E. Sparks, Mail Drop 54, 919/541-2458. For presentation at 7th Int. Conf. IAQ and Climate. Nagoya, Japan, 7/21-26/1996.

16. ABSTRACT The paper discusses modeling volatile organic compound (VOC) emissions from indoor latex paint applied to gypsum board. Small chamber emissions studies have demonstrated that the substrate played an important role in determining the rate of VOC emissions from interior latex paint. An empirical source model for a porous substrate was developed that takes both the wet- and dry-stage emissions into consideration. Tests in the U.S. EPA's Source Characterization Laboratory showed that common interior surfaces such as gypsum board and carpet could adsorb significant amounts of latex paint VOCs from the air, and that they were re-emitted very slowly. An indoor air quality model incorporating the source model, an irreversible sink model, and the air movement data obtained from tracer gas tests made satisfactory predictions for the VOC levels in a test house.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Volatility	Pollution Control	13B	20M
Mathematical Models	Substrates	Stationary Sources	12A	11D
Latex	Gypsum	Latex Paint	11J	08G
Paints		Gypsum Board	11C, 13C	
Emission		Volatile Organic Compounds (VOCs)	14G	
Building Boards			11L	
Organic Compounds		Indoor Air Quality	07C	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	**Unclassified**	
	20. SECURITY CLASS *(This page)* **Unclassified**	22. PRICE

EPA Form 2220-1 (9-73)